RADRUE method for reconstruction of individual doses for not observed persons in the accident on Chernobyl nuclear power plant

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Abstract. A retrospective assessment of individual doses for persons, for whom there were no radiation monitoring in the accident on Chernobyl NPP was carried out. At most it was the population of the town Pripyat and the liquidators who worked in the early days of the accident. A new method of photon (i.e., gamma and x rays) dose assessment, called RADRUE (Realistic Analytical Dose Reconstruction with Uncertainty Estimation), was developed to calculate this doses. The RADRUE program implements a time-and-motion dose-reconstruction method that is flexible and conceptually easy to understand. It includes a large exposure rate database and interpolation and extrapolation techniques to calculate exposure rates. The RADRUE technique relies on data collected from subjects' interviews conducted by trained interviewers, and on expert dosimetrists to interpret the information and provide supplementary information, when necessary, based upon their own Chernobyl experience.

1. RADRUE METHOD

Between 1986 and 1990, several hundred thousand workers, called "liquidators" or "clean-up workers," took part in decontamination and recovery activities within the 30-km zone around the Chernobyl nuclear power plant in Ukraine, where a major accident occurred in April 1986. The Chernobyl liquidators were mainly exposed to external ionizing radiation levels that depended primarily on their work locations and the time after the accident when the work was performed. Because individual doses were often monitored inadequately or were not monitored at all for the majority of liquidators, a new method of photon (i.e., gamma and x rays) dose assessment, called "RADRUE" (Realistic Analytical Dose Reconstruction with Uncertainty Estimation) 1, was developed to obtain unbiased and reasonably accurate estimates for use in three epidemiologic studies of hematological malignancies and thyroid cancer among liquidators. The RADRUE program implements a time-and-motion dose-reconstruction method that is flexible and conceptually easy to understand. External exposure dose D received by the individual for some time in the radiation field can be represented as the sum of products of several variables:

$$D = C\sum_{i=1}^{n} P(x(t_i), y(t_i), t_i) \cdot \Delta t_i \cdot L_i , \quad (1)$$

where $P(x(t_i),y(t_i),t_i)$ – exposure dose rate ($mR \cdot h^{-1}$) in a place, where the liquidator at the t_i moment of time was. C – conversion factor from the exposure dose to the value we are interested - absorbed dose, particularly in the red bone marrow.[1] Coordinates $x(t_i)$, $y(t_i)$ describe localization of the liquidator at the moment of time t_i; n - number of time intervals Δt_i (not necessarily equal) during which the dose rate can be considered constant. L_i – the place factor.

The most part of initial data for the doses reconstruction we received from the interviews with liquidators. Specially trained interviewers who had an experience in the liquidation of Chernobyl consequences, interviewed the liquidators and then filled out a questionnaire, containing a large number of clarifying questions about its route, circumstances of work and residence.

Then, questionnaires were studied by experts-dosimetrists (former members of the CNPP Department of retrospective reconstruction of doses), who have acquired considerable experience in liquidators' dose evaluation by the 1997 and who could evaluate the reliability of data reported by the liquidator. It was supposed that experts can restore any work performed by the liquidators in detail being based on the accumulated knowledge about the circumstances of different groups of liquidators and on the personal experience of participation in the liquidation of Chernobyl consequences.

At present the program includes a large database on the radiation situation in 70 km zone around CNPP from 26.04.1986 to 1990. Being based on this data, we will restore doses of persons who were not monitored at all or who were monitored only partially.

2. EXTERNAL DOSES OF WITNESSES OF THE ACCIDENT

The first group of injured (27 persons) has arrived to the emergency department of 6th Clinical Hospital (Moscow) at 6.50a.m. 27.04.86 year, Table1. 102 more persons have been delivered to the hospital on the same day at 5.30p.m., and the third group (21 persons) has been delivered on the 28.04.86 year at 12.00p.m. In first three days since the accident 299 persons have been sent to the 6th Hospital USSR Ministry of Health and to the Kiev Hospitals with a preliminary diagnosis of ARS. 224 persons have passed through the 6th Hospital in 1986 due to irradiation in the accident and to liquidation of the Chernobyl accident [2].

Table 1. Dynamics of number of hospitalized persons to the Medical Unit-126 and the 6th Clinical Hospital

Moment of time	Medical unit-126 (Pripyat)	6-th Clinical Hospital (Moscow)
26.04.86, 02 h 10 min	1	-
26.04.86, 04 h 30 min	60	-
26.04.86, 10 h 00 min	98	-
26.04.86, 14 h 00 min	132	-
27.04.86, 06 h 50 min		27
27.04.86, 17 h 30 min		129
28.04.86, 12 h 00 min		150

[1] RADRUE method was developed primarily for estimation of liquidators' doses - cases and controls from case-control studies of radiation-induced leucosis.

Doses have been restored for 158 injured of Chernobyl accident from the number of CNPP employers and liquidators who have arrived to the hospital in the end of April 1986. Dose estimation on a red bone marrow of injured was carried out using earlier developed in the Institute of Biophysics method - on the number of dicentrics per 100 cells and on the dose-effect curve previously obtained from the studies of patients with acute leucosis in remission period. In the chromosome aberration analysis the data of the dicentric chromosomes output were used. The own chromosome aberrations dose-effect curves were used in work, they were obtained from the cytogenetic analysis of peripheral blood lymphocytes and bone marrow of patients with leucosis undergoing total body irradiation during the preparation for bone marrow transplantation period [3]. Subsequently doses defined by the chromosomal aberration were confirmed by subsequent clinical condition of these persons and the results of hematological tests (the nature of the dynamics of neutrophils in the blood). These doses got to a range from 0,1 to 13,7 Gy. Doses have been estimated as zero for 26 surveyed persons. Injured' dose distribution is shown in Table 2.

Table 2. Dose distribution of the accident's witnesses.

Dose, Gy	0-1	1-2	2-4	4-6	6-8	> 8
Number of persons	71	17	34	15	6	15

For all patients, of the 6th Hospital, whose actions and route sheets were examined in our study, the dose of chromosomal aberrations were identified in 1986. It allowed comparing these doses with doses calculated by RADRUE method. It should be noted that the doses of liquidators, determined by the chromosomal aberration in the 6th Clinical Hospital are one of the most reliable parameters and these doses are considered as reference in comparison with the results of the RADRUE method, see Table 3.

Table 3. Comparison of doses evaluated by RADRUE method (mathematical expectation) with doses evaluated by chromosomal aberration.

Category of staff	Employeers' name	Dose on red bone marrow according to RADRUE, Gy	Mean geometrical deviation	Duration of exposure	Dose according to aberrations, Gy
Firemen	V.S.	2,9	2,81	1h 50min	2,8
	M.A.	0,17	3,32	4h 25 min	0,8
	V.N.	19,4	2,72	1h 10 min	11,1
	S.L.	3,7	2,04	0h 20 min	4,7
	V.P.	10,6	2,38	0h 45 min	13,7
	N.I.	25,2	2,09	1h 30 min	12,5
Personnel of turbine shop of the 2d stage	Y.A.	4,5	4,53	1h 27 min	7,5
	R. T.	3,1	4,69	1h 08 min	3,6

		Y.V.	2,7	4,11	1h 57 min	7,1
		A.M.	6,6	3,87	2h 52 min	8,7
		V.G.	4,1	4,91	5h 20 min	4,2
Personnel of different shops of CNPP		N.F.	1,6	4,62	6h 40 min	1,5
	Chemical shop	S.A.	0,03	2,73	2h 47 min	0,2
	Administration	A.S.	3,6	2,91	4h 20 min	5,5
		E.A.	3,7	2,88	1h 07 min	8,3
		A.I.	0,26	3,35	6h 50 min	0,8
Builders		V.I.	3,0	2,95	6h 37 min	3,2
Member of the armed forces from CNPP's guard		I.	0,82	1,81	4h 30 min	0,9
		I.G.	3,5	2,75	4h 15 min	2,1
Medical Unit-126 staff		A.A.	0,05	2,57	4h 00 min	0,2

2.1 Drivers from Kiev

By the Government commission (formal decision was made at 12 o'clock in the afternoon) it was decided to evacuate the population of Pripyat on the 27 April, on the next day after the accident.
Vehicles intended for the evacuation, focused on secondary and field roads between Ivankov and Chernobyl towns until further notice. 1,200 buses and 200 onboard cars have arrived by 7 o'clock on April 27. At 13 h 10 min convoy of buses escorted by traffic police special vehicles entered the town of Pripyat. At the entrance to the town of Pripyat was a great traffic jam that stretched for several kilometers and crossed the radioactive trail in a 4-kilometer zone.
By means of RADRUE program, the distribution of air kerma was calculated on the drivers route with the following assumptions:

- the traffic jam stretched from the border of Pripyat on 2 km 800m,
- the time spent in a traffic jam was as follows: 1 hour waiting in the open air and 1 hour waiting in the bus,
- the coefficient of bus' protection was taken to be 0.29.

Parameters of the calculated air kerma distribution are resulted in the fourth line of Table 4. As can be seen from the table, drivers waiting the entrance to Pripyat could receive a dose comparable to the maximum permissible emergency dose (250 mGy), or even surpassing it. With probability 0.9 air kerma didn't surpass 650 mGy that excludes the possibility of ARS.
The main place of drivers' exposure from Kiev – is the crossing of highway Pripyat-Chernobyl and radioactive trace.

2.2 Public catering workers

The Head of refectory "Elektronika" A.I. and the handyman M.Y. on April 26 from 6 o'clock 30 minutes to 14 o'clock 30 minutes were on the refectory's territory «for protection of property» by order of the Head of supply department A.D. The first person was dealt with the documentation and was inside the building, and the second one was cleaning the refectory's courtyard and was basically outdoors, at the open air. According to the RADRUE program the dose rate at the cafe's area was 175 R/h.
Parameters of the air kerma distribution of injured woman, which are given in the first line of Table 4, are calculated on the assumption that the worker was inside the building all the time and "protection of property" lasted during 8 hours, the coefficient of protection of the building is equal to 0.07.
If we assume that the injured man at least 10% of time was in the open air than the median of the air kerma distribution would increase from 0.52 Gy to 1.2 Gy. If he was indoors only 30% of the time, than the median of distribution would increased to 5.4 Gy.
The dose of A.I. has been defined on unstable chromosome aberrations in the 6th Clinical Hospital and was equal to 0.67 Gy. With regard to M.Y, he has dropped out of sight of public health services (died in 1988).

2.3 Passengers of the railway trains passing through the station Yanov

As known, before the Chernobyl accident, the trains followed through the station Yanov (Pripyat) at the road from Zhitomir to Chernigov. On traverse to CNPP these trains were just at a distance of 740 m from fourth power-generating unit of CNPP. Therefore, the question on doses which could be received by the passengers of these trains on April 26th, 1986 is logical.
By means of RADRUE program, the air kerma distribution was calculated with the following assumptions:

- rate of train on the way from the station Yanov to Railroad Bridge over the Pripyat River was 22,5 km / h,
- the coefficient of train's protection was taken to be equal to the coefficient of protection of the lorry or the bus (0.29).

Parameters of the air kerma distribution are given in the second line of Table 4. As can be seen from the table, the passengers received doses less than 10 mGy with a probability of 0.9.

2.4 Doses, received by the residents of Pripyat during the evacuation

Evacuation route from the Pripyat passed through the axis of radioactive trace in a 4-km zone around CNPP. Exposure rate on the axis of the trace many times surpassed exposure rate in Pripyat. Therefore, the dose received by inhabitants during the evacuation could be a significant addition to the dose received by inhabitants of Pripyat since the moment of accident on 26 April until the evacuation on 27 April 1986. By means of RADRUE program, the air kerma distribution was calculated with the following assumptions:

- buses' speed on the way from the centre of Pripyat to the board of 4-km zone was 25 km/h,
- the coefficient of bus' protection was taken to be 0,29.

Parameters of the calculated air kerma distribution during the evacuation are resulted in the fifth line of Table 4. Kerma for residing at Pripyat from the moment of the accident till evacuation was calculated at following assumptions:

- On April, 26th, 1986 the resident was outdoors during 5h, and indoors during 17h,
- On April, 27th, 1986 the resident was outdoors during 3h, and in and indoors during 11h.

Parameters of air kerma distribution during the residence in Pripyat are resulted in the sixth line of Table 4. As it is possible to see from comparison, the dose for evacuation makes approximately 25 % from a dose for residing before evacuation.
The basic place of the evacuated residents' irradiation, as well as the drivers from Kiev, is the intersection of highway Pripyat-Chernobyl with radioactive trace.

2.5 "Forgotten" residents of Pripyat

As it is known, not all residents of Pripyat were evacuated on April, 27th, 1987 from Pripyat. Operations staff lived in the city for a few days more and only then was transferred to a summer camp "Skazochniy." In addition to operating personnel in the vicinity of Pripyat was a sports centre watchman's family who had forgotten to evacuate because of its secluded residence. This family consisted of husband, wife and children; they were evacuated only on May 5. Sports centre was located about 500 meters from the border of Pripyat.
By means of RADRUE program, the air kerma distribution for "forgotten" residents was calculated with the following assumptions:

- "forgotten" people all the time were near the sports centre,
- the coefficient of dwelling house's protection was taken to be 0.29,
- "forgotten" residents were in the sports center from April 26 to May 5, 1986,
- time spent outdoors was equal to time spent indoors.

Parameters of air kerma distribution for "forgotten" residents of Pripyat are resulted in the third line of Table 4. From the data resulted in the table follows that the irradiation of this family is characterized by clinically significant doses.

Table 4. Parameters of air kerma distribution for different groups of the accident's witnesses.

Category of the accident's witnesses	Parameters of air kerma distribution			
	Median, Gy	Arithmetic mean, Gy	90% percentile, Gy	β
"Elektronika" refectory worker (indoors)	0,52	1,06	2,3	3,22
Passengers of trains	0,0031	0,0046	0,0096	2,34
"Forgotten" residents of Pripyat	0,36	0,62	1,30	2,70
Buses' drivers	0,098	0,28	0,65	4,25
Evacuation of Pripyat	0,0067	0,010	0,021	2,53
Residents of Pripyat	0,023	0,038	0,078	2,67
Potential exposure of the residents of Pripyat	0.30	0.49	1.00	2.50

2.6 Potential exposure of the residents of Pripyat

Naturally the question arises: What could be the dose of the residents of Pripyat at the highest unfavorable scenario -if the radioactive trace would pass directly through the Pripyat town? It's possible to answer this question by means of RADRUE program, if to combine by rotation of topographic map up to combining the center of the town Pripyat with the axis of the radioactive trace. Dose calculated for the moved by this way zone will be the highest possible dose for Pripyat.

Parameters of the highest possible air kerma distribution for residents of Pripyat are resulted in the seventh line of Table 4. As it is possible to see, in this case doses of residents would reach significant values at a mode of behavior of residents taking place in a reality before evacuation – approximately in 50 % of all cases these doses would surpass maximum permissible doses for professionals in case of radiological accident. However, it should be noted that in case of a strict restriction of exit to the open air, these doses could be kept at the dose level received by residents of Pripyat in real. The biggest potential irradiation could be received by the residents in the streets of Pripyat.

3. CONCLUSION

Thanks to the primary data about circumstances of work collected in the Institute of Biophysics Clinic and in the CNPP Department of retrospective reconstruction of doses and also to application of RADRUE method it was possible to restore doses of injured and witnesses of the accident, residents of Pripyat and some other categories of persons which were exposed to radiation in the first day of the accident.

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